

Instability of QCD ghost dark energy model

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We investigate the instability of the ghost dark energy model against perturbations in different cases. To this goal we use the squared sound speed v_s^2 whose sign determines the stability of the model. When $v_s^2 < 0$ the model is unstable against perturbation. At first we discuss the noninteracting ghost dark energy model in a flat FRW universe and find out that such a model is unstable due to the negativity of the v_s^2 in all epoches. The interacting ghost dark energy model in both flat and non-flat universe are studied in the next parts and in both cases we find that the squared sound speed of ghost dark energy is always negative. This implies that the perfect fluid for ghost dark energy is classically unstable against perturbations. In both flat and non flat cases we find that the instability of the model increases with increasing the value of the interacting coupling parameter.

I. INTRODUCTION

Nowadays, there are enough observational evidences which indicate that our universe is currently experiencing a phase of acceleration [1–5]. The unknown cause of this unexpected acceleration called “dark energy” (DE) whose nature is still a matter of much doubt. Trying to explain observed acceleration of the universe expansion two main approaches have been followed in the literatures. The first is based on the DE proposal which assumes that there exist an exotic form of energy with negative pressure which is responsible for the acceleration of the universe expansion. Famous alternatives in this approach including cosmological constant Λ , scalar field models of DE such as quintessence [6, 7], K-essence [8–10], phantom fields [11], tachyon [12], holographic DE [13] and agegraphic DE [14] and so on (for a recent

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review on DE models see [15] and references therein). The second approach for explanation of the acceleration expansion is based on the modification of the gravity theory. In this approach the DE problem is considered as a shortcoming of the Einstein's gravity and try to modify the standard model of cosmology in such a way that the phase of acceleration is reproduced without including any new kind of energy. Examples of these models are $f(R)$ gravity [16, 17] and braneworld scenarios [18, 19].

Seeking a solution to $U(1)$ problem, the so-called Veneziano ghost has been proposed in the low energy effective QCD where they are completely decoupled from the physical sector [20–23]. The ghosts make no contribution in the flat Minkowski space, but make a small energy density contribution to the vacuum energy due to the off-set of the cancelation of their contribution in curved space or time-dependent background. This contribution to the vacuum energy density can be considered a possible candidate for the origin of the cosmological constant [24]. In a dynamic background or a spacetime with non-trivial topology the ghost field contributes to the vacuum energy proportional to $\Lambda_{QCD}^3 H$, where H is the Hubble parameter and Λ_{QCD} is QCD mass scale. With $\Lambda_{QCD} \sim 100 MeV$ and $H \sim 10^{-33} eV$, $\Lambda_{QCD}^3 H$ gives the right order of magnitude $\sim (3 \times 10^{-3} eV)^4$ for the observed DE density [24]. This remarkable coincidence implies that the ghost dark energy (GDE) model is free from the fine tuning problem [24, 25]. It was shown that this vacuum energy density can play the role of DE in the evolution of the universe [26, 27].

Every new model of DE represents new features and consequences which should be explored carefully. One way to test the viability of a new DE model is to explore its stability against perturbations. To investigate the stability, a key quantity is the squared speed of sound $v_s^2 = dp/d\rho$ [28]. The sign of v_s^2 plays a crucial role in determining the stability of the background evolution. If $v_s^2 < 0$, it means the classical instability of a given perturbation. This issue has already been investigated for some DE models. It was shown that chaplygin gas and tachyon DE have positive squared speeds of sound with, $v_s^2 = -w$, and thus they are supposed to be stable against small perturbations [29, 30]. However, the perfect fluid of holographic DE with future event horizon is classically unstable because its squared speed is always negative [31]. Also in [32], it is shown that the agegraphic model of DE have a negative sound speed squared in flat, non-flat and also in the presence of interaction indicating the instability of this model against perturbations.

DE and dark matter (DM) are usually considered as two distinct dark components of

the universe due to their unknown nature and very different origin of them. Note that DM has gravity effect and plays a crucial role in explanation of the galaxy rotation curve, while DE has anti-gravity feature which pushes the universe and makes its expansion accelerated. However, in recent years several signals have been detected, implying a small interaction between DE and DM is possible. As an instance, observational evidences provided by the galaxy cluster Abell A586 supports the interaction between DE and DM [33]. Beside that, lately there arose an interest in the non-flat version models of DE in literature. This new enthusiasm originates from some observations which challenge the idea of the flat universe. For example evidences from CMB and also supernova measurements of the cubic correction to the luminosity distance favor a positively curved universe [34, 35]. In addition, some exact analysis of the WMAP data reveals the possibility of a closed universe [36].

All above reasons motivate us to study the stability of interacting GDE model in a nonflat universe. In this paper, we would like to generalize the approach presented in [28, 31, 32] to GDE model in a universe with spacial curvature in the presence of interaction between the dark matter and DE. Various aspects of GDE have recently been investigated. A thermodynamical description of GDE is discussed in [37]. Tachyon and quintessence reconstruction of GDE model were studied in [38] and [39] respectively. The study has also been extended to Brans-Dicke theory [40].

This paper is organized as follows. In the next section, we review the GDE model in both flat and nonflat universe. In section III, we explore the stability of the GDE model in all discussed cases of section II. We summarize our results in section IV.

II. A BRIEF REVIEW ON GHOST DARK ENERGY

A. Noninteracting ghost dark energy

Let us at first review the noninteracting GDE in a flat FRW background filled with a matter component and GDE. We follow the method of [27]. Dynamic of such a universe is determined by the Friedmann equation

$$H^2 = \frac{1}{3M_p^2} (\rho_m + \rho_D), \quad (1)$$

where ρ_m is the energy density of pressureless DM and ρ_D is the GDE density. According to standard cosmology one can define the fractional density of different energy components

of the universe as

$$\Omega_m = \frac{\rho_m}{\rho_{cr}}, \quad \Omega_D = \frac{\rho_D}{\rho_{cr}}, \quad (2)$$

where the critical energy density is $\rho_{cr} = 3H^2 M_p^2$. Thus, the Friedmann equation can be rewritten as

$$\Omega_m + \Omega_D = 1. \quad (3)$$

Here, we consider the GDE which its energy density can be written as [24]

$$\rho_D = \alpha H, \quad (4)$$

where α is a constant of order Λ_{QCD}^3 and Λ_{QCD} is QCD mass scale. Based on the definition of Ω_D and using (4), we get

$$\Omega_D = \frac{\rho_D}{\rho_{cr}} = \frac{\alpha}{3M_p^2 H}. \quad (5)$$

Energy conservation equations for different components read

$$\dot{\rho}_m + 3H\rho_m = 0, \quad (6)$$

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = 0. \quad (7)$$

Taking the time derivative of relation (4), and using the Friedmann equation (1) as well as the continuity equation (7) we find

$$\frac{\dot{\rho}_D}{\rho_D} = \frac{\dot{H}}{H} = -\frac{3}{2}H[1 + \Omega_D w_D]. \quad (8)$$

Substituting this relation in continuity equation (7) we obtain the equation of state (EoS) parameter of GDE, namely

$$w_D = -\frac{1}{2 - \Omega_D}. \quad (9)$$

Evolution of w_D versus Ω_D is shown in Fig.1. One finds that at the early time where $\Omega_D \ll 1$ we have $w_D = -1/2$, while at the late time where $\Omega_D \rightarrow 1$ the GDE mimics a cosmological constant, namely $w_D = -1$. Another interesting quantity to be calculated is the deceleration parameter

$$q = -1 - \frac{\dot{H}}{H^2} = \frac{1}{2} - \frac{3}{2} \frac{\Omega_D}{(2 - \Omega_D)}. \quad (10)$$

From above relation it is clear that at the late time where $\Omega_D \rightarrow 1$, $q = -1$. At the early universe where $\Omega_D \rightarrow 0$ we have $q = 1/2$, which corresponds to the matter dominated epoch. Evolution of q versus Ω_D is plotted in Fig.2. Two important points should be emphasized

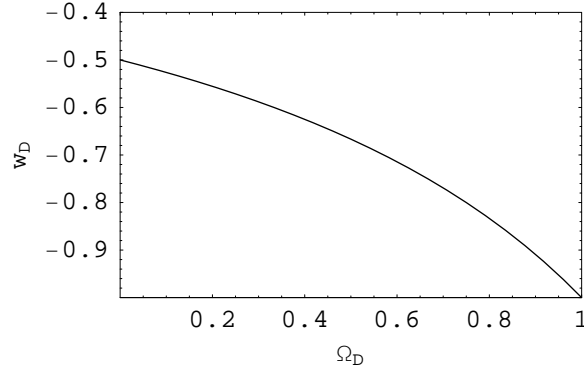


FIG. 1: Evolution of w_D versus Ω_D for noninteracting GDE.

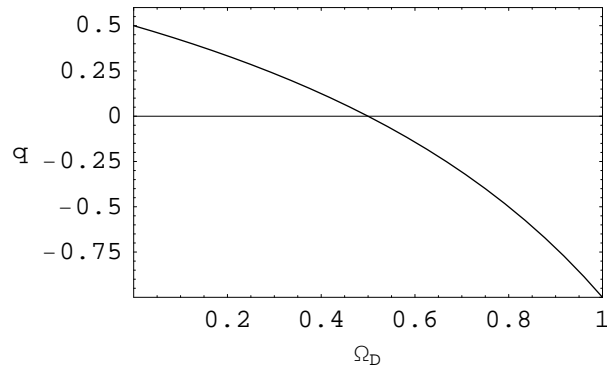


FIG. 2: Evolution of deceleration parameter against Ω_D for noninteracting GDE.

for noninteracting GDE model. First, in this model there exist no free parameter. Second, w_D cannot cross the phantom line. The evolution of GDE is governed by [27]

$$\Omega'_D = 3\Omega_D \left(\frac{1 - \Omega_D}{2 - \Omega_D} \right), \quad (11)$$

where the prime denotes the derivative with respect to $x = \ln a$.

B. Interacting ghost dark energy

DM and DE are usually considered separately in the modern cosmology. However, there exist some observational evidences which support an interaction between them [41]. Thus, it seems meaningful to study the interacting version of GDE. To this goal we start with energy conservation equations

$$\dot{\rho}_m + 3H\rho_m = Q, \quad (12)$$

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = -Q. \quad (13)$$

In these equations the form of Q has not been chosen exactly yet, however, we know that Q should be small and positive. A large and positive choice of Q does not lead to late time acceleration while a large and negative choice of Q will lead to an early domination of DE component which does not let the large structures to be formed in the universe. One should note that a choice of negative sign for Q implies decaying of DE to the cold DM. In this paper we choose the interaction term as $Q = 3H^2(\rho_D + \rho_M)$ which can be written as $Q = 3H^2\rho_D(1 + \frac{\Omega_M}{\Omega_D})$. In the case of interacting, the EoS parameter is obtained as [27]

$$w_D = -\frac{1}{2 - \Omega_D} \left(1 + \frac{2b^2}{\Omega_D} \right). \quad (14)$$

Setting $b = 0$, w_D for the noninteracting case is retrieved. In the late time where $\Omega_D \rightarrow 1$, the EoS parameter of interacting GDE necessary crosses the phantom line, namely, $w_D = -(1 + 2b^2) < -1$ independent of the value of coupling constant b^2 . Also the deceleration parameter can be calculated as [27]

$$q = \frac{1}{2} - \frac{3}{2} \frac{\Omega_D}{(2 - \Omega_D)} \left(1 + \frac{2b^2}{\Omega_D} \right). \quad (15)$$

The equation of motion of Ω_D can be obtained as

$$\frac{d\Omega_D}{d \ln a} = \frac{3}{2} \Omega_D \left[1 - \frac{\Omega_D}{(2 - \Omega_D)} \left(1 + \frac{2b^2}{\Omega_D} \right) \right]. \quad (16)$$

C. Interacting ghost dark energy in non-flat universe

In the past decade several observational evidences have been observed in contrast to the flatness assumption of the universe. In the context of inflation which assumes a large rate of expansion at the beginning instants of the evolution of the universe, it is argued that the flatness is not a necessary consequence of inflation if the number of e-folding is not very large [42]. Besides, the parameter Ω_k represents the contribution to the total energy density from the spatial curvature and it is constrained as $-0.0175 < \Omega_k < 0.0085$ with 95% confidence level by current observations [43]. These motivate us to study the GDE model in the presence of curvature. Taking the curvature into account, the first Friedmann equation is written as

$$H^2 + \frac{k}{a^2} = \frac{1}{3M_P^2} (\rho_m + \rho_D). \quad (17)$$

This equation can be written as

$$\Omega_m + \Omega_D = 1 + \Omega_k, \quad (18)$$

where $\Omega_k = \frac{k}{a^2 H^2}$. We can obtain different parameters in the presence of the curvature term. Taking the time derivative of the Friedmann equation (17) and using (18), we find

$$\frac{\dot{H}}{H^2} = \Omega_k - \frac{3}{2} [1 + \Omega_k + \Omega_D w_D]. \quad (19)$$

Combining the above equation with Eq. (13), after using $Q = 3H^2 \rho_D (1 + \frac{\Omega_M}{\Omega_D})$, as well as $\frac{\dot{\rho}}{\rho} = \frac{\dot{H}}{H}$ we obtain the EoS parameter as

$$w_D = -\frac{1}{2 - \Omega_D} \left(1 - \frac{\Omega_k}{3} + \frac{2b^2}{\Omega_D} (1 + \Omega_k) \right). \quad (20)$$

The deceleration parameter can be calculated by substituting Eqs. (19) and (20). We find

$$q = \frac{1 + \Omega_k}{2} + \frac{3\Omega_D}{2(2 - \Omega_D)} \left[1 - \frac{\Omega_k}{3} + \frac{2b^2}{\Omega_D} (1 + \Omega_k) \right]. \quad (21)$$

Also the equation of motion of GDE can be obtained as [27]

$$\frac{d\Omega_D}{d \ln a} = \frac{3}{2} \Omega_D \left(1 + \frac{\Omega_k}{3} - \frac{\Omega_D}{2 - \Omega_D} \left[1 - \frac{\Omega_k}{3} + 2b^2 \Omega_D^{-1} (1 + \Omega_k) \right] \right). \quad (22)$$

It is worth mentioning that all relations we obtained in this subsection restore their respective expressions in the previous subsection when we set $\Omega_k = 0$.

III. INSTABILITY OF THE GHOST DARK ENERGY

The main idea for investigating the stability of GDE model comes from the perturbation theory. Assuming a small perturbation in the background energy density, we would like to see if the perturbation grows or will collapse. In the linear perturbation theory, the perturbed energy density of the background can be written as

$$\rho(t, x) = \rho(t) + \delta\rho(t, x), \quad (23)$$

where $\rho(t)$ is unperturbed background energy density. The energy conservation equation ($\nabla_\mu T^{\mu\nu} = 0$) yields [28]

$$\delta\ddot{\rho} = v_s^2 \nabla^2 \delta\rho(t, x), \quad (24)$$

where $v_s^2 = \frac{dP}{d\rho}$ is the squared of the sound speed. Solutions of equation (24) include two cases of interest. First when v_s^2 is positive Eq. (24) becomes an ordinary wave equation whose its solutions would be oscillatory waves of the form $\delta\rho = \delta\rho_0 e^{-i\omega t + i\vec{k}\cdot\vec{x}}$ which indicates a propagation mode for the density perturbations. The second is when v_s^2 is negative. In this case the frequency of the oscillations becomes pure imaginary and the density perturbations will grow with time as $\delta\rho = \delta\rho_0 e^{\omega t + i\vec{k}\cdot\vec{x}}$. Thus the growing perturbation with time indicates a possible emergency of instabilities in the background.

In what follows, we are trying to see if the GDE leads to instabilities in the FRW background. To this end we will calculate the sound speed for both interacting and noninteracting GDE model.

A. Instability of noninteracting ghost dark energy

In this section we would like to obtain the sound speed in a background filled with matter and GDE in the absence of interaction. The squared sound speed can be written as

$$v_s^2 = \frac{dP}{d\rho}. \quad (25)$$

In order to obtain the sound speed in a background filled with barotropic fluids we rewrite the definition as [26]

$$v_s^2 = \frac{dP}{d\rho} = \frac{\dot{P}}{\dot{\rho}} = \frac{\rho}{\dot{\rho}} \dot{w} + w, \quad (26)$$

where in the last step we have used $P = w\rho$. Taking time derivative of Eq.(4) and using (7), we obtain

$$\frac{H}{\dot{H}} = \frac{\rho}{\dot{\rho}} = \frac{-2}{3H(1 + \Omega_D w_D)} \quad (27)$$

Inserting (9), into above relation we get

$$\frac{\rho}{\dot{\rho}} = -\frac{2 - \Omega_D}{3H(1 - \Omega_D)} \quad (28)$$

Taking the time derivative of (9) yields

$$\dot{w}_D = -\frac{\dot{\Omega}_D}{(2 - \Omega_D)^2}. \quad (29)$$

Replacing Eqs.(28) and (29) into (26) and also using (11) we get

$$v_s^2 = -2\frac{1 - \Omega_D}{(2 - \Omega_D)^2}, \quad (30)$$

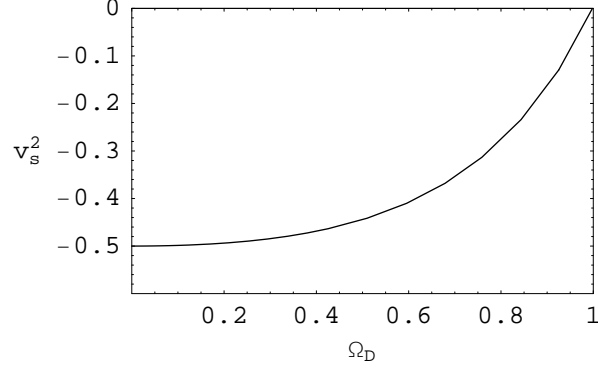


FIG. 3: Evolution of squared sound speed v_s^2 against Ω_D for noninteracting GDE model.

where we also used $\frac{d}{dt} = H \frac{d}{d \ln a}$. This result is the same as one presented in [26]. Having the v_s^2 at hand we are ready to discuss about the stability of perturbations. It is clear that in the evolution history of the universe Ω_D can achieve values in the range $[0, 1]$ which $\Omega_D = 0$ indicates beginning stages of the evolution of the universe while $\Omega_D = 1$ is an extrapolation of the future of the universe. One can easily see from (30) that v_s^2 is always negative and varies between $[-\frac{1}{2}, 0]$. Hence, Eq. (24) has solution of the second category ($\delta\rho = \delta\rho_0 e^{\omega t + i\vec{k} \cdot \vec{x}}$). This result indicates that due to the negativity of the squared sound speed every small perturbation can grow with time which leads to an instability in the universe. Thus we cannot expect a noninteracting GDE dominated universe in the future as the fate of the universe. The evolution of the v_s^2 versus Ω_D is shown in Fig. 3.

B. Instability of interacting ghost dark energy

A same steps as the pervious section can be followed to obtain the squared sound speed v_s^2 for the interacting case. Taking time derivative of Eq. (14) we have

$$\dot{w}_D = -\frac{\dot{\Omega}_D}{(2 - \Omega_D)^2} \left[1 + \frac{4b^2}{\Omega_D^2} (\Omega_D - 1) \right]. \quad (31)$$

Also from (8) one finds

$$\frac{\rho}{\dot{\rho}} = -\frac{2}{3H(1 + \Omega_D w_D)}. \quad (32)$$

Taking into account relation $\frac{d}{dt} = H \frac{d}{d \ln a}$ as well as (16) yields

$$\dot{\Omega}_D = \frac{3}{2} H \Omega_D \left[1 - \frac{\Omega_D}{(2 - \Omega_D)} \left(1 + \frac{2b^2}{\Omega_D} \right) \right]. \quad (33)$$

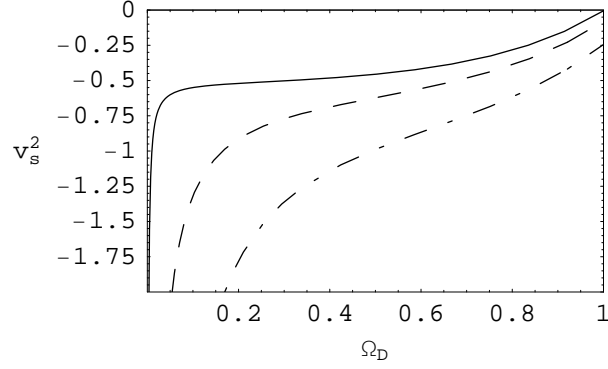


FIG. 4: This figure shows evolution of squared sound speed v_s^2 versus Ω_D for interacting GDE model. The solid line corresponds to $b = 0.05$, dashed line to $b = 0.2$ and dashed-dot line to $b = 0.35$.

Replacing these relations in (26) and after a little algebra one obtains

$$v_s^2 = -2 \frac{1 - \Omega_D}{(2 - \Omega_D)^2} + 2b^2 \frac{3\Omega_D - 4}{\Omega_D(2 - \Omega_D)^2}, \quad (34)$$

which is the squared sound speed for interacting GDE fluid. The evolution of v_s^2 against Ω_D is plotted in Fig. (4) for different values of the coupling parameter b . The figure reveals that v_s^2 is always negative and thus, as the previous case, a background filled with the interacting GDE seems to be unstable against the perturbation. This implies that we cannot obtain a stable GDE dominated universe. One important point is the sensitivity of the instability to the coupling parameter b . The larger b , leads to more instability against perturbations.

C. Instability of interacting ghost dark energy in non-flat universe

Finally, we study the instability of interacting GDE model in a universe with spacial curvature. From Eq. (19) we can obtain

$$\frac{\rho}{\dot{\rho}} = \frac{-2}{3H \left[1 + \frac{\Omega_k}{3} - \frac{\Omega_D}{2 - \Omega_D} \left(1 - \frac{\Omega_k}{3} + \frac{2b^2}{\Omega_D} (1 + \Omega_k) \right) \right]} \quad (35)$$

Taking the time derivative of Eq. (20), yields

$$\dot{w}_D = \frac{\dot{\Omega}_D}{2 - \Omega_D} \left[-\frac{1}{2 - \Omega_D} \left(1 - \frac{\Omega_k}{3} + \frac{2b^2}{\Omega_D} (1 + \Omega_k) \right) + \frac{2b^2}{\Omega_D^2} (1 + \Omega_k) \right] \quad (36)$$

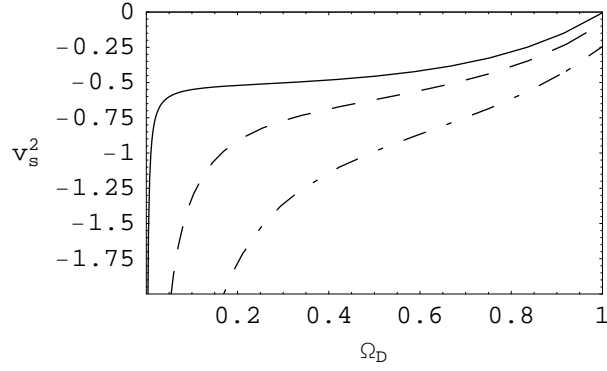


FIG. 5: This figure shows evolution of squared sound speed v_s^2 versus Ω_D for interacting GDE model in a nonflat background. The solid line corresponds to $b = 0.05$, dashed to $b = 0.2$ and dashed-dot line to $b = 0.35$.

Having the above relations at hand we are in a position to obtain the squared sound speed v_s^2 . Replacing Eqs. (35), (36) in (26), after using (22), one gets

$$v_s^2 = -\frac{2(1 - \Omega_D)}{(2 - \Omega_D)^2} + \frac{2}{3} \frac{1 - \Omega_D}{(2 - \Omega_D)^2} \Omega_k + \frac{2b^2}{\Omega_D} \frac{3\Omega_D - 4}{(2 - \Omega_D)^2} (1 + \Omega_k). \quad (37)$$

Setting $\Omega_k = 0 = b$ the above relation reduces to the flat noninteracting respective relation. Also the squared sound speed of the flat interacting case can be retrieved when $\Omega_k = 0$.

In order to obtain an insight on the stability issue of the interacting GDE in a nonflat FRW universe, we have to discuss on the sign of v_s^2 during the evolution of the universe. To this end we plot v_s^2 versus Ω_D , where the value of Ω_D indicates different epoches of evolution. The result can be seen in Fig. 5 which clearly indicates an almost same behavior as the flat interacting case. For all epoches the squared sound speed, (v_s^2) , is negative indicating the instability of the universe against perturbations in the GDE background. Once again we see the crucial dependence of the stability to the coupling parameter b . Increasing b will result more instability in the universe which is clearly seen in Fig. 5. As a result the universe filled with DM and GDE even in the presence of the curvature cannot lead to a stable GDE dominated universe.

IV. SUMMARY AND DISCUSSION

Every new DE model should at first explain the acceleration of the universe expansion whose EoS parameter satisfies $w_D < -1/3$. If the model passed this test, then it should

be investigated for further features and consequences. Since we know from observation that our stable universe is experiencing a phase of acceleration due to the domination of DE (assuming the DE approach for explanation of the acceleration of the universe is correct), thus every new DE model should be capable to lead a stable DE dominated universe. Thus the investigation on the stability of a proposed DE model is well motivated. Among various DE model the so called QCD ghost DE model was recently proposed to explain the DE dominated universe within the framework of standard model of particle physics and general relativity. It was argued that the vacuum energy of the Veneziano QCD ghost field in a time-dependent background can play the role of DE with an energy density proportional to the Hubble parameter H [24]. The advantages of this new proposal compared to the previous DE models is that it is totally embedded in standard model so that one needs not to introduce any new parameter, new degree of freedom or to modify general relativity [26].

In this paper we have explored the stability of the GDE model against perturbations in the flat/nonflat background and with/without interaction. We used the squared sound speed ($v_s^2 = \frac{dP}{d\rho}$) as the main factor for studying the stability. If v_s^2 is positive the GDE would be stable against perturbations. When v_s^2 is negative we encounter the instability in the background spacetime. We have discussed several cases including whether there is or not an interaction between DM and GDE and whether there is or not a curvature term in the background metric. Interestingly enough, we found that the GDE model is always unstable against perturbations. As a result, the universe filled with DM and GDE component cannot lead to a stable GDE dominated universe. We also observed that the instability of the interacting GDE increases with increasing the interacting coupling parameter b .

Acknowledgments

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